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Hybrid FRP-concrete-steel double-skin tubular columns: Cyclic axial compression tests

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Abstract

Hybrid FRP-concrete-steel double-skin tubular columns (hybrid DSTCs) are a new form of hybrid columns recently developed at The Hong Kong Polytechnic University. A hybrid DSTC consists of an inner steel tube, an outer FRP tube and a concrete infill between the two tubes. Hybrid DSTCs possess many important advantages over existing column forms, including their excellent corrosion resistance and excellent seismic resistance. While a large amount of research has been conducted on the monotonic behavior of this novel form of columns, only a limited amount of work has been conducted on their behavior under cyclic loading. This paper presents the first experimental study on hybrid DSTCs under cyclic axial compression, with a particular emphasis on the effect of different cyclic loading schemes and on the behavior of the confined concrete. Hybrid DSTCs are shown by these tests to be very ductile under cyclic axial compression, with an envelope axial load-strain curve being almost the same as the axial load-strain curve of a corresponding DSTC under monotonic compression. It is also shown that repeated unloading/reloading cycles have a cumulative effect on the permanent strain and the stress deterioration of the confined concrete in hybrid DSTCs.

Keywords

axial, cyclic, compression, tests, tubular, columns, skin, double, steel, concrete, frp, hybrid

Disciplines

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HYBRID FRP-CONCRETE-STEEL DOUBLE-SKIN TUBULAR COLUMNS: CYCLIC AXIAL COMPRESSION TESTS

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Abstract

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Keywords: concrete, cyclic compression, FRP, hybrid columns, steel, tubular columns.

1. Introduction

Hybrid FRP-concrete-steel double-skin tubular columns (DSTCs) are a new form of hybrid columns recently proposed by the fourth author [1-2] at The Hong Kong Polytechnic University (PolyU). Such a column consists of an outer tube made of fibre-reinforced polymer (FRP) and an inner tube made of steel, with the space between filled with concrete (Figure 1). The inner void may be filled with concrete if desired. The FRP tube is provided with fibers which are predominantly oriented in the circumferential direction to provide confinement to the concrete and additional shear resistance. In this new hybrid column, the three constituent materials are optimally combined to achieve several important advantages, including their excellent corrosion resistance and excellent seismic resistance. A large amount of research has recently been completed at PolyU on the monotonic behaviour of hybrid DSTCs, through laboratory testing of small-scale columns subjected to axial compression [3], bending [4] and combined bending and compression [5] as well as finite element modeling [6-7]. A design-oriented stress-strain model for the confined concrete in hybrid DSTCs subjected to monotonic axial compression has also been proposed [8].

Existing studies conducted at PolyU on hybrid DSTCs have been limited to monotonic loading. As a structural form particularly suitable for use in seismic regions, the behavior of hybrid DSTCs subject to cyclic loading is of particular importance. This paper presents the results of a series of cyclic axial compression tests on hybrid DSTCs as part of an on-going project aiming to develop a procedure for the seismic design of these columns. To the best of the authors' knowledge, no existing studies have been concerned with hybrid DSTCs under cyclic axial compression.

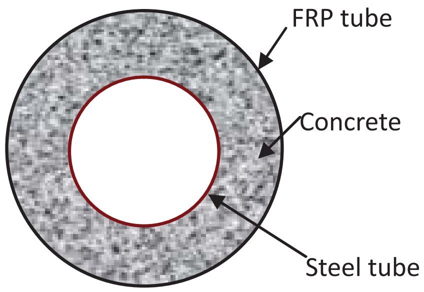


Figure 1. Cross section of hybrid FRP-concrete-steel double-skin tubular column

2. Experimental Program

2.1 Test Specimens

In total, eight identical hybrid DSTCs were tested, covering four loading schemes; two specimens were prepared for each loading scheme. The specimens had an outer diameter (i.e. the outer diameter of the annular concrete section) of 205.3 mm, an inner diameter (i.e. the inner diameter of the annular concrete section and the outer diameter of the inner steel tube) of 140.3 mm, and a height of 400 mm. The outer glass FRP (GFRP) tube had fibers in the hoop direction only and was formed by a wet-layup process on hardened concrete [2]. The nominal thickness of the two-ply FRP tube was 0.34 mm (i.e. the nominal thickness was taken to 0.17 mm per ply) while the thickness of the steel tube was 5.3 mm.

2.2 Material Properties

Tensile tests on steel coupons cut from the same long steel tube that provided the individual short steel tubes for the DSTCs were conducted. These tests showed that the steel had a yield stress of 325.5 MPa, a tensile strength of 431.6 MPa, and a Young's modulus of 195.6 GPa. In addition, three hollow steel tubes also cut from the same original long tube were tested under monotonic axial compression (for two of the three tubes) or cyclic axial compression (for one of the three tubes). All the three tubes failed by local buckling in the elephant's foot mode and the average ultimate load of these tubes was 832.1 kN. The slope of the unloading/reloading path in the stress-strain curve found from the cyclic axial compression test was almost the same as the elastic modulus of the steel (i.e. no stiffness degradation). The FRP used here had an average tensile strength of 1781 MPa and an average Young's modulus of 104.3 GPa based on a nominal thickness of 0.17mm per ply. The elastic modulus, compressive strength and compressive strain at peak stress of the concrete averaged from three concrete cylinder tests (152.5 mm x 305 mm) were 31.8 GPa, 43.9 MPa and 0.00264 respectively.

2.3 Experimental Set-up and Instrumentation

For each hybrid DSTC specimen, two bi-directional strain rosettes (gauge length = 10 mm) were installed at the mid-height of the steel tube and four bi-directional strain rosettes (gauge length = 20mm) were installed at the mid-height of the FRP tube (Figure 2). In addition, four linear variable displacement transducers (LVDTs) were used to obtain the axial deformation of the middle region of 160 mm for each specimen. All compression tests were carried out using an MTS machine with a displacement control rate of 0.24 mm/min. All test data, including the strains, loads, and displacements, were recorded simultaneously by a data logger.

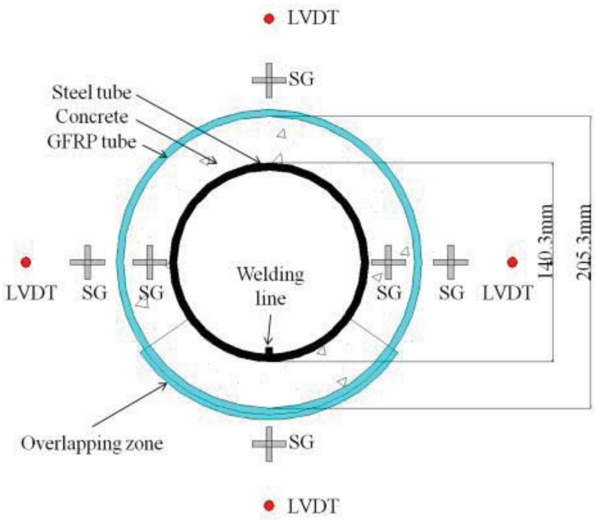


Figure 2. Experimental instrumentation.

2.4 Loading Schemes

Two of the eight specimens (i.e. specimens M1 and M2) were tested under monotonic axial compression while the other six were tested using three different cyclic loading schemes. Among the six cyclic loading specimens, specimens F1 and F2 were designed for cyclic compression involving full unload/reloading cycles, where the unloading of each cycle was designed to terminate at zero (or a near-zero) load and the reloading of each cycle was designed to terminate at the unloading displacement of the same cycle (i.e. where the unloading started) or after reaching the envelope curve [9]; specimens PU1 and PU2 were designed for partial unloading cycles where the unloading of each cycle was terminated at a load level significantly larger than zero while the termination point of reloading was the same as a full unloading/reloading cycle; specimens PR1 and PR2 were designed for partial reloading cycles where the reloading of each cycle was terminated before reaching the unloading displacement of the same cycle while the termination point of unloading was the same as a full unloading/reloading cycle. The load level at which the unloading was terminated in a partial unloading cycle and the displacement level at which the reloading was terminated in a partial reloading cycle were designed based on results from the tests on specimens F1 and F2 so that the conditions of effective unloading/reloading cycles defined by Lam and Teng [9] were satisfied.

For each of the six specimens, the unloading/reloading cycles were designed to be started at five prescribed unloading displacement values which were selected based on results from the tests of specimens M1 and M2 under monotonic axial compression so that the first unloading strain is between 0 and 0.001, the second unloading strain is between 0.001 and 0.0035, and the last three unloading strains are larger than 0.0035 and are evenly distributed on the axial load-strain curve. The three distinctive ranges of unloading strain were determined according to an existing study conducted at PolyU [9] on the cyclic compressive behavior of confined concrete at different levels of plastic deformation. Three repeated unloading/reloading cycles were imposed at the first four unloading displacements while six repeated cycles were imposed at the subsequent unloading displacements. All the loading schemes were automatically executed by a computer program with the use of the displacement and load readings of the MTS machine as the controlling parameters. It should be noted that the displacement output of the MTS machine included not only the shortening of the specimen but also the deformation of the whole loading system. In the testing process, the loading scheme was duly adjusted for some of the specimens according to the results from the preceding test specimens. The final loading schemes are summarized in Table 1.

Table 1. Loading schemes.

Specimen Step	F1	F2	PU1	PU2	PR1		PR2	
	Unloading displacement (mm)							
1	0.40	0.60	0.60	0.60	0.60	0.54[*]	0.60	0.54[*]
2	1.20	1.20	1.20	1.20	1.20	1.08[*]	1.20	1.08[*]
3	2.59	2.59	2.59	2.59	2.59	2.35[*]	2.59	2.35[*]
4	3.98	3.98	3.98	3.50	3.50	3.17[*]	3.50	3.17[*]
5	5.37	5.37[^]	5.37	4.50	4.50	4.15[*]	4.50	4.15[*]
	Reloading load (kN)							
1	20[#]	20[#]	100	100	20[#]		20[#]	
2	20[#]	20[#]	145	145	20[#]		20[#]	
3	20[#]	20[#]	180	180	20[#]		20[#]	
4	20[#]	20[#]	205	205	20[#]		20[#]	
5	20[#]	20[#]	210	210	20[#]		20[#]	

Note: [*]Unloading displacement of the subsequent loading cycles (i.e. termination point of the preceding reloading path);

[^] The specimen failed during the first unloading/reloading cycle at this unloading displacement;

[#] 20kN was selected instead of 0 kN for a more stable control of the MTS machine

3. Results and Discussions

3.1 General Behavior

As expected, all the specimens failed by the rupture of the GFRP tube at or near the mid-height, without any obvious buckling deformation in the inner steel tube. The specimens after test are shown in Figure 3 while the axial load-axial strain curves are shown in Figure 4, where the axial strains were found from the LVDT readings.

It is evident from Figure 4 that the envelope curves of the three pairs of specimens subjected to cyclic compression, which provide an upper boundary of their responses under cyclic loading, are almost the same as the monotonic axial load-strain curves of specimens M1 and M2. The slightly lower envelope curve for specimen PR2 was found to be due to a deficiency in the preparation of the specimen: the steel tube was slightly inclined and thus the concrete layer thickness was slightly non-uniform along the column height.

Figure 4 also shows that the unloading/reloading cycles at the same prescribed unloading displacement generally do not coincide with each other, indicating that the effect of repeated loading cycles (or loading history) on the cyclic response of the hybrid DSTC is not negligible. The difference between two consecutive loading cycles, however, becomes increasingly small with the number of repeated cycles.

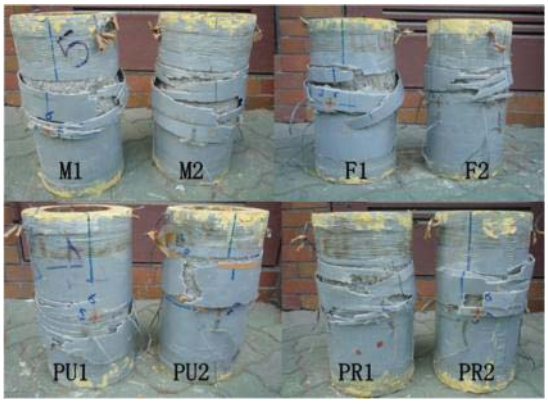
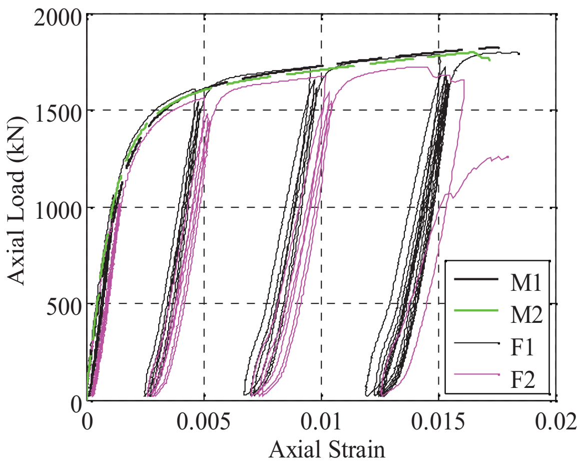
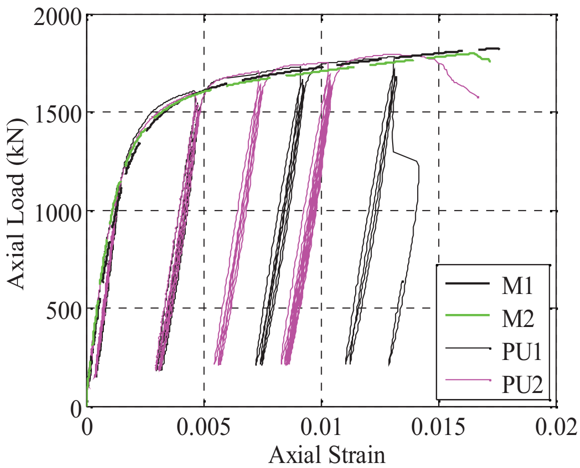


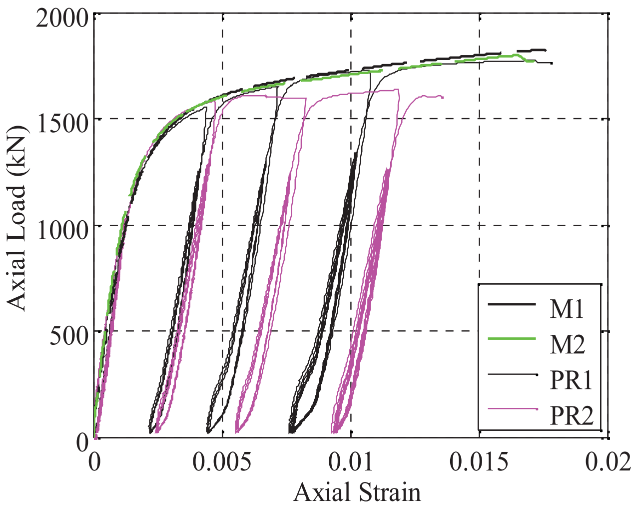
Figure 3. Specimens after test.



(a) Specimens M1, M2, F1 and F2.



(b) Specimens M1, M2m PU1 and PU2.



(c) Specimens M1, M2, PR1 and PR2.

Figure 4. Axial load-axial strain curves.

3.2 Strain Compatibility between the Concrete and the Steel Tube

The plastic axial strain (referred to as "plastic strain" hereafter) of a material is its residual axial strain when it is unloaded to zero stress. When the steel tube and the concrete of a hybrid DSTC are both axially strained to a value considerably larger than the yield strain of steel, the plastic strain component of the concrete is generally much smaller than that of the steel tube because the nonlinearity of concrete is largely an effect of material damage (i.e. degradation in stiffness) while that of steel depends almost solely on plasticity. Consequently, during the unloading process, the steel tube reaches zero stress first before the axial load reduces to zero; when the axial load is completely removed, tensile stresses are expected to develop in the steel tube together with equilibrating compressive stresses in the concrete. It is likely that some bond slips occur between the two materials, in which case the steel tube has shortened more (i.e. has a smaller compressive strain) than the concrete when the axial load is completely released. As a result, when the DSTC is reloaded, the concrete is directly loaded right from the beginning and deforms until the steel tube comes into contact with the loading plates when the two materials will again have the same strain. Figure 5 shows the axial strains of the concrete found from the LVDTs versus those of the steel tube found from the strain gauges for specimen F2. The comparison (especially the last two loading cycles) clearly illustrates the phenomenon discussed above.

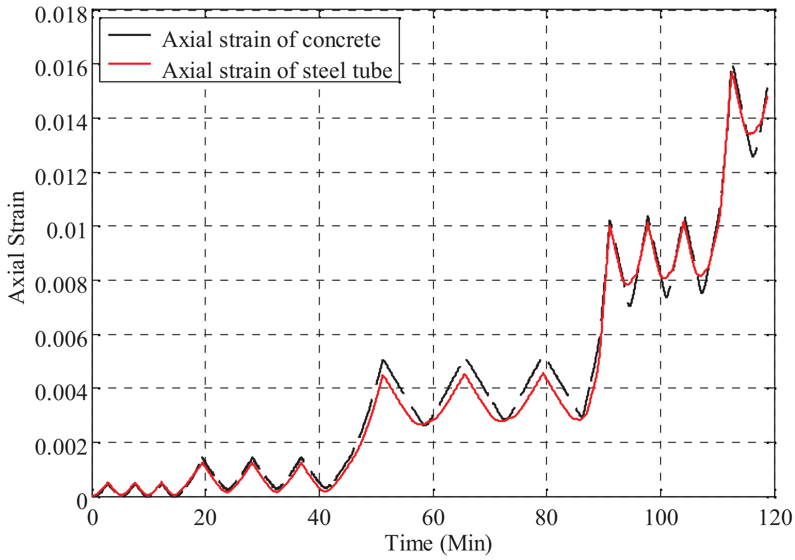


Figure 5. Axial strains of concrete and steel tube.

The above discussions also suggest that the axial strain at which the load carried by a hybrid DSTC is zero is not necessarily (in most cases larger than) the plastic strain of the concrete, and is always smaller than the plastic strain of the steel tube.

3.3 Axial Stress-Strain Curves of Concrete

The envelope axial stress-strain curves of the confined concrete in all the test specimens are shown in Figure 6 while the cyclic axial stress-strain curves of specimens F1 and F2 are compared in Figure 7. The axial stress of concrete in a DSTC is defined as the load carried by the annular concrete section divided by its cross-sectional area. The load carried by the concrete section is assumed to be equal to the difference between the load carried by the DSTC specimen and that carried by the steel tube; the latter was found based on results of the compression tests on hollow steel tubes. After the steel tube reaches zero stress during unloading, if its axial strain decreases further, it is assumed that tensile stresses are developed in the steel tube and the ratio between the stress increment and the strain increment is equal to the unloading modulus of steel found from the cyclic compression test of hollow steel tube. Figure 6 shows that except for that of specimen PR2, the envelope curves of all the other five specimens subjected to cyclic axial compression are almost the same as the monotonic axial stress-strain curves of specimens M1 and M2. The slightly lower envelope curve for specimen PR2 was found to be due to a deficiency in the preparation of the specimen: the steel tube was slightly inclined and the concrete layer thickness was thus slightly non-uniform along the column height.

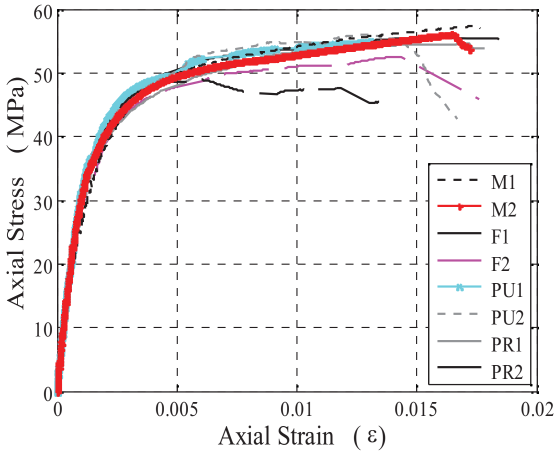


Figure 6. Envelope axial stress-strain curves.

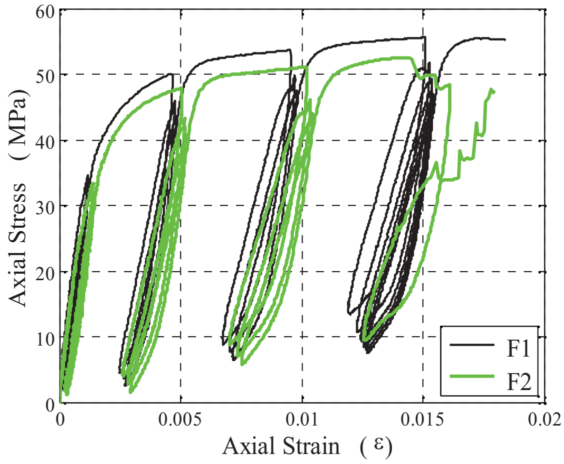


Figure 7. Cyclic axial stress-strain curves of specimens F1 and F2.

Similar to the findings shown in Figure 4, Figure 7 indicates that the effect of loading history on the cyclic response of the confined concrete in a hybrid DSTC is not negligible. Instead, the loading history has a cumulative effect on both the plastic strain and the stress deterioration of the confined concrete. Figure 7 also shows that the difference between two consecutive loading cycles becomes increasingly small with the number of repeated cycles. These observations agree well with the findings of existing studies on unconfined concrete, steel-confined concrete an FRP-confined concrete [9], and further confirm that the uniqueness concept proposed by Sinha et al. [10] cannot apply here. The uniqueness concept means that the locus of common points, where the reloading path of an unloading/reloading cycle crosses the unloading path, can be considered as a stability limit. It is also interesting to note that while specimens F1 and F2 were subjected to full unloading/reloading cycles (i.e. unloading was terminated at zero or a very small load), the axial stresses in the concrete at the termination points of unloading are significantly higher than zero; these compressive stresses in the concrete exist to equilibrate the tensile stresses in the steel tube as discussed earlier.

4. Conclusions

This paper has presented a series of cyclic axial compression tests on hybrid DSTCs. Hybrid DSTCs have been shown to be very ductile under cyclic loading and their envelope axial load-strain curves are almost the same as the corresponding monotonic axial stress-strain curve. It has also been shown that repeated unloading/reloading cycles have a cumulative effect on the permanent strain and the stress deterioration of the confined concrete in hybrid DSTCs. Interfacial slips between the steel tube and the concrete may lead to noticeable differences in the axial strain between them when the column is fully unloaded from an axial strain level that significantly exceeds the yield strain of the steel tube.

5. Acknowledgements

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